CRITICAL PLANE ANALYSIS OF WALL ASSEMBLY IN A HOT, HUMID CLIMATE

STEPHEN C. TURNER, PE, CIAQP PRINCIPAL CHELSEA GROUP LTD. PROVIDENCE, RI

ABSTRACT

Condensation plane analysis for determining critical planes at which condensation may occur can be performed for building assemblies in any climate. Procedures for doing so in heating climates where buildings dry to the outside of envelope assemblies are given in 1997 ASHRAE Fundamentals Handbook, Chapter 22 "Thermal and Moisture Control in Insulated Assemblies – Fundamentals."[1] Little original work is available elsewhere in the literature to guide analysis for buildings in hot and humid climates.

Example 1 in Chapter 22 of the Fundamentals Handbook gives step-by-step calculations, for a heating climate.[1] To analyze envelope assemblies in hot and humid climates where drying predominately occurs to the indoors, no direct discussion or examples are available. This paper presents this detail for a typical light commercial wall assembly, and provides the basis for analysis of any envelope assembly in hot and humid climates.

Analysis of an envelope assembly in hot and humid climates seeks to determine if there is a critical plane in the wall towards which water vapor flows more rapidly from the outdoors than it flows to the indoors. (In heating climates, the analysis is reversed). In order to do this, weather data must be examined to yield outdoor conditions, and indoor conditions must be identified. Water vapor and thermal resistance of the materials in the wall assembly must also be established. These data are then used to perform calculations using the basic diffusion equation and methods described in the Fundamentals Handbook.[1] Each potentially critical plane is analyzed to determine if water vapor can accumulate more rapidly than it dissipates. This potential accumulation would signify a heightened risk of equilibrium relative humidity sufficient to amplify microbial growth, or to promote the deterioration of building materials.

METHODS

Critical plane analysis calculations were performed for a wall assembly with the following components from outside to inside: vinyl acrylic paint, 5/8" stucco, 8" concrete block, 1" batt between 3/4" furring strips, and 1/2" gypsum board. The analysis shows that, at every plane within the wall, moisture is always able to flow more rapidly to the indoors than it is able to accumulate from the outdoors. The analysis shows no opportunity for excessive moisture vapor to accumulate in the wall due to moisture migration driven by the vapor pressure differential across the wall assembly. This analysis has been performed under carefully selected conditions to represent the worst prolonged conditions that could be expected.

The critical plane analysis indicates that excessive moisture accumulation is unlikely in the wall assembly considered. This report details the procedures and results of this method for the given wall detail.

This analysis considers steady state conditions that are assumed to remain constant over prolonged periods of time. While these results give valuable insight into the mechanisms for moisture transport, they should be evaluated with the realization that real world conditions may change rapidly over a wide range. This analysis considers the effects of vapor potential across the wall assembly as driven by outdoor and indoor air temperature and relative humidity, but not certain extreme conditions that may exist sporadically, or that may arise from envelope failure and resulting bulk water intrusion.

Within the limitations of this analysis, the results show that condensation in the intact wall assembly is unlikely to result in moisture accumulation.

ANALYSIS

The first step in analyzing wall performance with respect to water vapor penetration is to determine conservative conditions that represent plausible real world conditions. Conservative outdoor and indoor conditions are determined from available weather data and estimated indoor operating conditions.

Units

Permeability, the rate of transmission of vapor through a unit area of material per unit thickness induced by the vapor pressure difference between two parallel surfaces at a specified temperature & humidity is expressed in gr/(h*ft2*(in.Hg/in.)). Permeance, the rate of transmission of water vapor through a unit area of material is expressed in units of gr/(h*ft2*in.Hg). A perm is a specifically defined expression of permeance, reported as the transmittal of 1 grain per hour through 1 square foot of 1 inch thick material under a vapor pressure difference of 1 inch Hg.

1 perm = 1 gr/(h*ft2*in.Hg)
Water vapor resistance, the reciprocal of permeance, is expressed in reps, or (h*ft2*in.Hg) /gr. This is a particularly useful unit in analysis, and is used in Table 1 and subsequent calculations and tables.

Outdoor Conditions
ASHRAE "bin" weather data, so called because the data list the occurrence of temperatures in 5°F ranges or bins during the year, are available for Tampa (see Appendix A). These data were examined to select conditions likely to produce the highest ambient vapor pressure in a southwestern Florida building.

High ambient vapor pressure will result in the highest vapor pressure differential across the wall assembly in a cooling climate. It is under these conditions that the force driving this mode of water vapor transport across the wall assembly is maximized. While the bin weather data suggest that ambient conditions with maximum water vapor pressure may occur at conditions in the range of 75°F dry-bulb, 74°F wet-bulb, analysis was performed under more rigorous conditions with higher ambient vapor pressure.

The dry-bulb temperature of 94°F is the upper range of the highest temperature range that is shown in the weather data. It exceeds 93°F, which is the "1 %" design dry-bulb temperature condition listed in the Fundamentals Handbook, Chapter 26.[1] This 1 % listing means that the temperature of 93°F was equaled or exceeded for 29 hours during the total hours (2928) in the months from June to September. Hence the choice of 94°F is a conservative choice for an upper sustained temperature value. By selecting this high air temperature for use in the analysis of condensation planes in the wall , the possible partial pressure of water vapor in the air is maximized.

At a given dry-bulb temperature, the water vapor pressure is maximized when relative humidity is highest. Mean coincident wet-bulb temperatures in the Fundamentals Handbook correspond to relative humidity between 51.65 to 53.55 %.[1] At conditions of 93°F dry-bulb and 78°F wet-bulb, the partial pressure of water vapor is 0.81 inches of mercury (in. Hg). This is derived from psychrometric data tabulated in the Fundamentals Handbook.[1]

Instead of using the 1 % design conditions, the water vapor pressure can be maximized by choosing a saturated, or 100 % relative humidity condition, for analysis. At 94°F dry-bulb, the partial pressure of water vapor in saturated air is 1.61 in. Hg.

Indoor Conditions
Indoor conditions must also be determined for analysis. The lower the dry-bulb temperature selected, and the lower the relative humidity in the space, the greater the vapor pressure difference across the wall assembly, and the more likely condensation becomes. However, it would be unreasonable to select a dry-bulb temperature lower than occupants will find desirable, or a relative humidity lower than the systems are able to maintain. The conditions selected for indoor analysis are 70°F dry-bulb temperature at 50 % relative humidity.

Moisture Migration
Under ASHRAE 1 % design conditions of 93°F dry-bulb temperature and 78°F wet-bulb temperature, the dew point of the outdoor air is 72.6°F. If the interior conditioned space and the interior wall surface are maintained below this temperature, condensation may be possible somewhere at the wall surfaces or within the wall assembly. If water vapor penetration is minimized by a vapor retarder at the outside surface of the wall, then the potential for condensation is reduced, since it is less likely that surfaces below dewpoint will contact moist air. If an effective exterior vapor retarder is not in place, but the wall assembly is sufficiently permeable by water vapor towards the inside to allow drying to the inside, then accumulation of water in the wall is unlikely to result. This is why guidance on construction in humid climates calls for greater vapor resistance at the outside surface and lower vapor resistance towards the inside.

Material Properties
Water vapor and thermal resistance of the materials in the wall assembly must be estimated. Resistance values are tabulated from the Fundamentals Handbook.

Table 1. Thermal and Vapor Resistances of Wall Assembly Materials

Material	Thermal Resistance per inch (1/k) (°F*ft²*h / Btu*in)	Thermal Resistance (R, or 1/C) (°F*ft²*h / Btu)	Vapor Resistance per inch (G) (rep/in) ((in.Hg*ft²*h / gr) / in)	Vapor Resistance (RV) (rep) (in.Hg*ft²*h/gr)
Outdoor moving air		0.25		-
Exterior acrylic		-		0.18
Vinyl-acrylic primer (2 coats)		-		0.24
Stucco		0.32	0.31	0.15
Concrete block, 8" normal		1.04		0.4
Kraft paper		-		0.028
Batt	4.00	4.00	0.0086	0.0086
Gypsum board, 1/2"		0.45		0.020
Primer		-		0.16
Semi-gloss paint		-		0.15
Indoor still air		0.68		0.0083

Table 2. Profile of Thermal and Vapor Resistances of Wall Assembly

Element	Thermal Resistance (R, or 1/C) (°F*ft²*h / Btu)	Vapor Resistance (RV) (rep, or in.Hg*ft²*h/gr)
Exterior stucco and paint	0.32	0.57
Concrete block	1.04	0.4
Kraft paper	-	0.028
Batt	4.0	0.0086
Drywall and paint	0.45	0.33

For the purposes of this analysis, the wall has five elements with vapor and thermal resistances as shown in Table Two. The exterior paint and stucco are considered as one element, with thermal resistance R = 0.32 (°F*ft²*h / Btu) and vapor resistance G = 0.57 ((in.Hg*ft²*h / gr) / in). The interior drywall and paint are another single element, with thermal resistance R = 0.45 and vapor resistance G = 0.33.

The thermal resistance values shown are for use in conjunction with this analysis only, and are not an accurate assessment of the overall R value of the wall. They do not include air interfaces or other elements that will increase the actual R value of the wall.

First the temperatures at each of the planes through the wall are calculated. The temperature drop to each plane is proportional to the thermal resistance of the wall to that point. This example calculation determines the temperature drop through the stucco and paint element.

$$\Delta t_1 = \frac{R_1}{R_{total}}(t_{out} - t_{in}) = \frac{0.32}{5.81}(94 - 70) = 1.3$$

The temperature drop through the stucco is 1.3°; the remaining temperature drops are calculated in similar fashion.

Table 3. Temperatures Throughout Wall Assembly

Location	Temperature	Saturation Vapor Pressure
Outdoor air temperature	94°F	1.6 in.Hg
Inside surface of stucco	92.7°F	1.5 in.Hg
Inside surface of concrete block	88.4°F	1.4 in.Hg
Inside surface of kraft paper	88.4°F	1.4 in.Hg
Inside surface of batt	71.9°F	0.79 in.Hg
Inside surface of drywall and paint (inside air temperature)	70°F	0.74 in.Hg
Inside condition	70°F	0.37 in.Hg

By comparing the vapor flow rates to each surface from the outdoors to the vapor flow rate leaving that surface to the indoors, each plane in the wall assembly can be evaluated to make sure that moisture can, in effect, leave that plane faster than it reaches it. If the flow from the surface to the indoors is greater than the flow from the outdoor to the surface, condensation is unlikely.

Surface Number One, Outside of Wall.
No analysis required.

Surface Number Two, Inside of Stucco.
Vapor resistance of wall to surface #2: 0.57 rep
Vapor pressure drop to surface #2: 1.6-1.5 = 0.1 in.Hg
Vapor flow to surface #2: 0.1/0.57 = 0.18 grains/h*ft^2

Vapor resistance of wall from surface #2 to indoors: 0.77 rep
Vapor pressure drop from surface #2 to indoors: 1.5-0.37 = 1.1 in.Hg
Vapor flow from surface #2 to indoors: 1.1/0.77 = 1.4 grains/h*ft^2

Surface Number Three, Inside of Block.
Vapor resistance of wall to surface #3: 0.97 rep
Vapor pressure drop to surface #3: 1.6-1.4 = 0.2 in.Hg
Vapor flow to surface #3: 0.2/0.97 = 0.21 grains/h*ft^2

Vapor resistance of wall from surface #3 to indoors: 0.37 rep
Vapor pressure drop from surface #3 to indoors: 1.4-0.37 = 1.0 in.Hg
Vapor flow from surface #3 to indoors: 1.0/0.37 = 2.7 grains/h*ft^2

Surface Number Four, Inside of Kraft Paper.
Vapor resistance of wall to surface #4: 1.0 rep
Vapor pressure drop to surface #4: 1.6-1.4 = 0.2 in.Hg
Vapor flow to surface #4: 0.2/1.0 = 0.20 grains/h*ft^2

Vapor resistance of wall from surface #4 to indoors: 0.34 rep
Vapor pressure drop from surface #4 to indoors: 1.4-0.37 = 1.0 in.Hg
Vapor flow from surface #4 to indoors: 1.0/0.34 = 2.9 grains/h*ft^2

Surface Number Five, Inside of Batt.
Vapor resistance of wall to surface #5: 1.0 rep
Vapor pressure drop to surface #5: 1.6-0.79 = 0.81 in.Hg
Vapor flow to surface #5: 0.81/1.0 = 0.81 grains/h*ft^2

Vapor resistance of wall from surface #5 to indoors: 0.33 rep
Vapor pressure drop from surface #5 to indoors: 0.79-0.37 = 0.42 in.Hg
Vapor flow from surface #5 to indoors: 0.42/0.33 = 1.3 grains/h*ft^2

Surface Number Six, Inside of Wall.
No analysis required.

Table 4. Results of Critical Plane Analysis

Surface #	Resistance of wall, outdoors to surface	Pressure drop, outdoors to surface	Flow, outdoors to surface	Resistance of wall, surface to indoors	Pressure drop, surface to indoors	Flow, surface to indoors	Flow difference
2	0.57 rep	0.1 in.Hg	0.18 grains/h*ft^2	0.77 rep	1.1 in.Hg	1.4 grains/h*ft^2	> 0, OK
3	0.97 rep	0.2 in.Hg	0.21 grains/h*ft^2	0.37 rep	1.0 in.Hg	2.7 grains/h*ft^2	> 0, OK

CONCLUSIONS

Limitations of Analysis

This analysis does not account for the possible vapor resistance of the bonding agent used to adhere the stucco to the block wall. If this material has high vapor resistance, then further analysis may reveal a critical plane where the stucco meets the block.

This analysis considers steady state conditions that are assumed to remain constant over prolonged periods of time. The results give valuable insight into the mechanisms for moisture transport. The results should be evaluated with the realization that real world conditions may change rapidly over a wide range.

This analysis considers the effects of vapor potential across the wall assembly as driven by outdoor and indoor air temperature and relative humidity. It does not consider certain extreme conditions that may exist sporadically. An example of such extreme conditions is freshly fallen rain that has saturated the exterior surface of the wall despite the resistance to permeance of the vinyl acrylic paint, which is then "boiled" into the wall by direct sunlight. The effects of radiant heat on the wall model in this case are not subject to analysis. However, the absence of an extremely high resistance vapor retarder anywhere in the wall assembly detail suggests that even in such cases, the wall will be able to dry to the inside.

Critical Plane Analysis

These calculations show that moisture is always able to flow more rapidly to the indoors than it is able to accumulate from the outdoors. There is no evidence of an opportunity for excessive moisture vapor to accumulate in the wall due to moisture migration driven by the vapor pressure differential across the wall assembly. This analysis has been performed under carefully selected conditions to represent the worst prolonged conditions that could be expected.

Parametric analysis of various wall assemblies can be performed using the same calculation methods applied to one typical wall assembly here. Such analysis reveals that, for a given envelope assembly in hot humid climates, decreased vapor resistance or increased thermal resistance towards the exterior of the assembly is potentially problematic. Brick, for example, having thermal resistance but lacking any significant vapor resistance, is not a logical choice for the exterior side of envelopes in hot humid climates.

Similarly, parametric analysis will show as potential problems either decreased thermal resistance or increased vapor resistance towards the interior of the assembly. This is why vinyl wallcoverings are to be avoided in hot humid climates.

The methods used in the analysis, since they represent the correct order and procedures for envelope analysis in cooling climates, can be applied to a variety of envelope assemblies for buildings in hot and humid climates.

[1] 1997. ASHRAE Handbook Fundamentals, ASHRAE, Atlanta.